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AN INTENSITY AND UNIFORMITY MONITOR FOR SOLAR SIMULATORS

B. A. McCullough, B. E. Wood, J. P. Dawson, et al.
ARO, Inc.

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FOREWORD

The research reported herein was sponsored by Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 61445014, Project 8951, Task 895104.

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In addition to the authors shown on the cover, R. C. Birkebak of Georgia Institute of Technology is an author of this report.

This technical report has been reviewed and is approved.

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ABSTRACT

An experimental study of a portable intensity and uniformity monitor for solar simulators is presented. The monitor is a modified integrating sphere coated with MgO and utilizes a thermopile as the detector. The radiation wavelengths used in evaluating the monitor were generated by a carbon arc solar simulator. These data were obtained as a function of time, intensity, temperature, and uniformity. The theory and operation of the monitor employed in these experiments are discussed. A modification of this monitor for use as a reflectometer is also presented.

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

A_d	Detector surface area, cm^2
A_e	Aperture surface area, cm^2
A_s	Interior surface area of a sphere, cm^2
A_t	Interior surface area of a truncated sphere, cm^2

A_v	Vehicle surface area, cm^2
I_o	Radiation intensity, w/cm^2
I_w	Relative intensity, I_o/Total I_o
k	Detector response constant, mv/w
r	Radius of aperture, cm
V_1	Detector response from the first reflection, mv
V_2	Detector response from the second reflection, mv
V_3	Detector response from the third reflection, mv
V_4	Detector response from the fourth reflection, mv
V_i	Detector response from i reflectance, mv
V_T	Detector response from the total reflection, mv
α	Slope of V_T versus I_o
ρ_v	Vehicle surface reflectance
ρ_w	Wall reflectance
ϕ	Position of the detector, deg

SECTION I
INTRODUCTION

Precise data on the thermal performance of a vehicle cannot be obtained in ground test facilities without accurate simulation of the major energy sources encountered in space. Since the sun is the main energy source in space, its simulation in space chambers is of prime interest (Refs. 1 through 4). The four major parameters which describe the performance of any solar simulator are (1) radiation intensity, (2) flux uniformity, (3) collimation angle, and (4) spectral distribution. The collimation angle is primarily a mechanical parameter in that it remains essentially constant after system installation is completed. However, the other three parameters are subject to change because of contamination or degradation of the optical characteristics of the system. For example, a lens or mirror system may become contaminated by the backstreaming from an oil diffusion pump or by outgassing from a surface. This could change the optical characteristics of the transfer system and introduce uncertainties in the spectral and intensity parameters. Therefore, these parameters should be monitored to ensure the validity of the test results.

The intensity of the radiation is normally measured with a calibrated thermopile. This system has several advantages over other measuring devices in that it is relatively portable, rugged, and requires only a simple readout system. The main disadvantages of this device are the potential sources of error that arise from the difference between conditions that may exist during calibration and actual tests such as: (1) temperature stability of the heat sink during irradiation, (2) "tare"* resulting from the unavoidable excess field of view and tare stability, and (3) energy losses caused by protective window (low-level calibration and high-intensity use).

Calorimetric techniques have also been used for measuring the total incident energy. These systems suffer from the same general problems associated with thermopiles. They also require precise metering of coolant flow during operation, and this results in another source of error.

The uniformity of the flux density may be measured with thermopiles or calorimeters. However, several difficulties also arise with these measurements. The coolant system required for these instruments complicates the scanning operation, and because of their slow response time, 20 to 30 min is required to survey a 6-ft line of a system. Solar cells or photovoltaic cells have rapid and linear response. These devices are used for

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*"tare" is the stray radiation striking the detector.

flux uniformity measurements. The main disadvantage is that they are normally quite small and the time required to map the uniformity of large solar simulators is much too great.

This report describes an intensity and uniformity monitor which eliminates or minimizes the potential sources of error previously described. The system does not require a coolant and will monitor a large area. The monitor is based on the principle of the integrating sphere in that the detector is irradiated by multiple reflections from the sphere wall. A discussion is given on the modification of the integrating sphere theory to correct for the large aperture. The effects of variable aperture, sphere size, and wall temperature variations are also discussed. The use of this system as a portable reflectometer for monitoring changes in vehicle surface reflectance and a discussion of tare stability are presented.

SECTION II
INTENSITY AND UNIFORMITY MONITOR

2.1 THEORY

The classical integrating sphere (Refs. 5 and 6) can be modified and used as an intensity monitor for a solar simulator (Ref. 7). Classical theory assumes that the interior wall of the sphere is uniformly irradiated by reflected radiation and that the wall is a perfectly diffuse reflector.

Consider a sphere (Fig. 1) of interior surface area A_s which has an aperture of radius r. The aperture cuts off an area A_e such that

$$A_s = A_t + A_e \tag{1}$$

where A_t is the interior surface area of the truncated sphere. Then the detector response can be formulated as follows.

Let collimated radiation of intensity I_o enter the aperture and illuminate the sphere. Then the area illuminated by the direct radiation is A_e, and the total energy is I_oA_e. The radiation reflected from a unit area would be $\rho_w I_o$ and the total radiation reflected would be $A_e\rho_w I_o$. Since this radiation is reflected diffusely, the irradiance on any unit area of sphere wall would be $(A_e\rho_w I_o)/A_s$, and the detector response from the first reflection, V_1, is

$$V_1 = (kA_d\rho_w I_o A_e)/A_s \tag{2}$$

where k is the detector response constant, A_d the detector area, and ρ_w

the wall reflectance. This assumes that the detector is not irradiated directly but only from reflected radiation.

Since $(A_e \rho_w I_o)/A_s$ radiation strikes each unit area of the sphere from the first reflection, the radiation reflected by each unit area would be $(A_e \rho_w^2 I_o)/A_s$. Thus, from second reflections, the detector response is

$$V_2 = (kA_d A_t A_e \rho_w^2 I_o)/A_s^2 \tag{3}$$

where A_t is the number of unit areas reflecting to the detector, assuming that A_d is smaller than A_t. Similarly, the detector response for the third reflection is

$$V_3 = (kA_d A_t^2 A_e \rho_w^3 I_o)/A_s^3 \tag{4}$$

and the fourth reflection is

$$V_4 = (kA_d A_t^3 A_e \rho_w^4 I_o)/A_s^4 \tag{5}$$

Then the detector response for all reflections would be

$$V_T = \sum_{i=1}^{n} V_i = \frac{kA_d A_e \rho_w I_o}{A_s} \left[1 + \frac{\rho_w A_t}{A_s} + \left(\frac{\rho_w A_t}{A_s}\right)^2 + \left(\frac{\rho_w A_t}{A_s}\right)^3 + \cdots \right] \tag{6}$$

or in closed form

$$V_T = \frac{kA_d A_e \rho_w I_o}{A_s} \left(\frac{1}{1 - \frac{\rho_w A_t}{A_s}} \right) \tag{7}$$

which upon rearrangement becomes

$$V_T = kA_d \rho_w I_o \left(\frac{A_e}{A_s - \rho_w A_t} \right) \tag{8}$$

Thus

$$V_T = \alpha I_o \tag{9}$$

for any given system and a plot of V_T versus I_o would give a straight line through the origin with a slope of α. This implies that a single calibration point will define the calibration curve for the system.

2.2 PROTOTYPE MONITORS

A monitor based on the integrating sphere technique was fabricated from a 3.5-in.-diam stainless steel sphere (Fig. 1). The entrance aperture was 1 in. in diameter and was equipped with a 6-in.-long, 1-in.-diam collimating tube. The interior of the collimating tube was coated with acetylene black, and the interior of the sphere was smoked with magnesium

oxide (MgO). The MgO surface meets the requirement for a diffuse reflecting wall (Ref. 8). Using the sun as a source of parallel light, the wall irradiance was measured as a function of position as determined by the angle ϕ (Fig. 1). This was accomplished by attaching calibrated solar cells to a rotating arm of appropriate curvature for mapping the wall irradiance. These experiments were repeated with MgO-coated spheres of 4, 6, and 8-in. diameters, all with a 1-in.-diam aperture. No change in wall irradiance was observed for any of the spheres. This indicates that the requirement (±2 percent) for uniform wall irradiance is met by such systems for A_s/A_e ratios from 50 to 256.

The rotating arm was replaced by a calibrated solar cell detector and a measurement of the wall irradiance was determined from the detector output. The energy source used in these experiments was a tungsten-iodine lamp, and the same detector was used for the different size spheres. These data (Fig. 2) were also obtained for the spheres with 2- and 3-in.-diam apertures. The solid line represents the detector output as calculated from Eq. (8). The data for the different diameter spheres and aperture sizes are represented by the designated symbols. These experiments show very good agreement between the theory and experimental data.

Based on the results obtained with the prototypes, an 8-in.-diam monitor with a 0.1-ft^2 aperture was fabricated (Fig. 3). Because of the temperature variations between the detector and its surroundings caused by radiation absorption, the exterior sphere surface was shielded by a reflector (Fig. 4). The aperture in the sphere was covered by a quartz plate to minimize convection losses. This system was calibrated using two sources, the sun and a carbon arc. The sensitivity of the system was 0.060 and 0.0585 mv/mw when the sun and the carbon arc, respectively, were employed. The carbon arc data are shown in Fig. 5 as a function of irradiance. Data are shown by symbols, and the solid line was calculated from Eq. (8). The constants in Eq. (8) were obtained from the data point corresponding to the detector output of 7 mv. The data for this sphere also agree very closely with theory. Figure 6 shows the variation of detector output with time. The dotted line represents the average output over a 12-min period. The 4-sec rotation of the carbon rod in the arc source can be observed in the detector output.

Three thermocouples, the locations of which are shown in Fig. 4, were used to monitor the temperature variations on the sphere during irradiation. These data are shown in Fig. 7. The slow steady rise in the thermopile base temperature as indicated in the figure would cause uncertainties in the detector output. The thermopile used here was not

temperature controlled; however, the uncertainties could have been minimized by using the coolant system.* If a thermopile detector such as described by Frazine (Ref. 9) were used, no coolant lines would be required, and the system would be more readily portable.

A monitor with a small aperture, i.e., 1/2-in. diameter, could be equipped with a filter wheel, and spectral distribution measurements could be obtained. The equations previously derived would not be altered, but care would have to be taken to incorporate the appropriate transmittance and sensitivity factors of the filters and detector to ensure accuracy.

2.3 MONITOR WITH VARIABLE APERTURE

A monitor with a variable entrance aperture would be more versatile than one with a large fixed aperture. It could not only obtain an integrated intensity over a large area but could also measure the distribution of intensity over this large area. If the system were a truncated sphere with a flat plate, which contained the variable aperture (Fig. 8), the irradiance within the sphere would not be uniform (Ref. 10). This is because the diffuse reflections from the flat plate, A (Fig. 8), would not uniformly irradiate the sphere walls. The intensity distributions for 1-, 2-, and 3-in.-diam apertures in a 5-in.-radius sphere, truncated with a 4-in. plate are shown in Fig. 9. The data points for values of ϕ less than 57 deg represent the intensity on the flat plate; those for ϕ larger than 57 deg show the intensity distribution on the walls of the truncated sphere. Similar calculations have also been obtained for 1.5-, 3-, 4-, 6-, and 7-in. radii. Equation (8), previously derived, cannot be applied to this type of system because the flat plate voids the assumption of uniform irradiance. However, any particular system could be calibrated.

SECTION III
PORTABLE REFLECTOMETER

If the reflectance characteristics of the surface of a test vehicle change because of contamination during a thermal balance test, test data may be lost unless the reflectance change could be monitored. The uniformity monitor previously described could be used for this purpose with a few minor changes. The changes would consist of placing another aperture opposite the source aperture such as shown in Fig. 10. The sample

*No data were taken with the cooling system operating (Fig. 3).

at A would be irradiated by the solar simulator through aperture B and the reflectance of the vehicle surface could be monitored. This would not be an absolute measurement since a standard would not be used, but relative changes in reflectance could be obtained by using a calibration curve. The reflectometer data would allow appropriate corrections to be made to the thermal balance data. However, large changes in the specular component of the reflectance of the vehicle surface could give misleading results. This would result from the reflectance becoming more diffuse, and the detector output would indicate an erroneous increase in reflectance. With proper calibration and experimental technique, the system could yield useful data on surface conditions and changes. This method could be made to yield absolute reflectance measurements by placing a known light source at B such as shown as an alternate source in Fig. 10. Then, following the standard integrating sphere procedures for reflectance measurements (Refs. 5 and 6), absolute values of total reflectance can be obtained.

Equation (8) may be modified to correct for the change in reflectance of the sample area. That is,

$$V_T = \frac{kA_d I_o \rho_v A_v}{A_s - [\rho_w (A_t - A_v) + \rho_v A_v]} \tag{10}$$

where ρ_V is the reflectance of the vehicle surface of area A_V.

SECTION IV
CONCLUDING REMARKS

It has been shown that a simple and accurate radiation intensity and uniformity monitor for large areas can be built and operated. The cost is considerably less than present models in use.

The system requires a minimum of hard line connections and no coolant, which simplifies installation. Calibration of the device can be made in situ, thus, minimizing the errors arising from remote calibration and transfer.

The monitor, with minor modifications, could be used as a portable reflectometer which could supply important data in heat balance and thermal testing.

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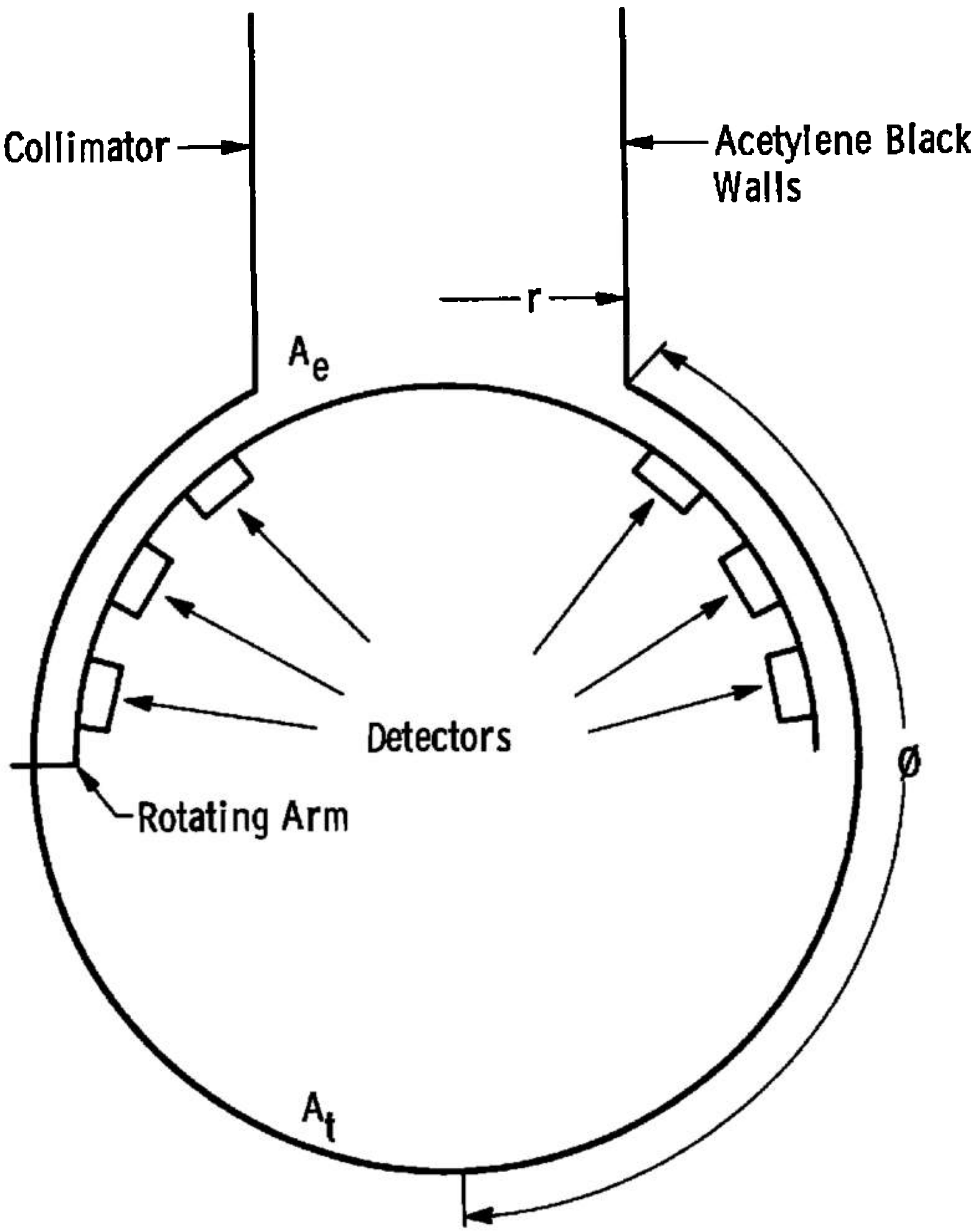


Fig. 1 Prototype Intensity Monitor Diagram

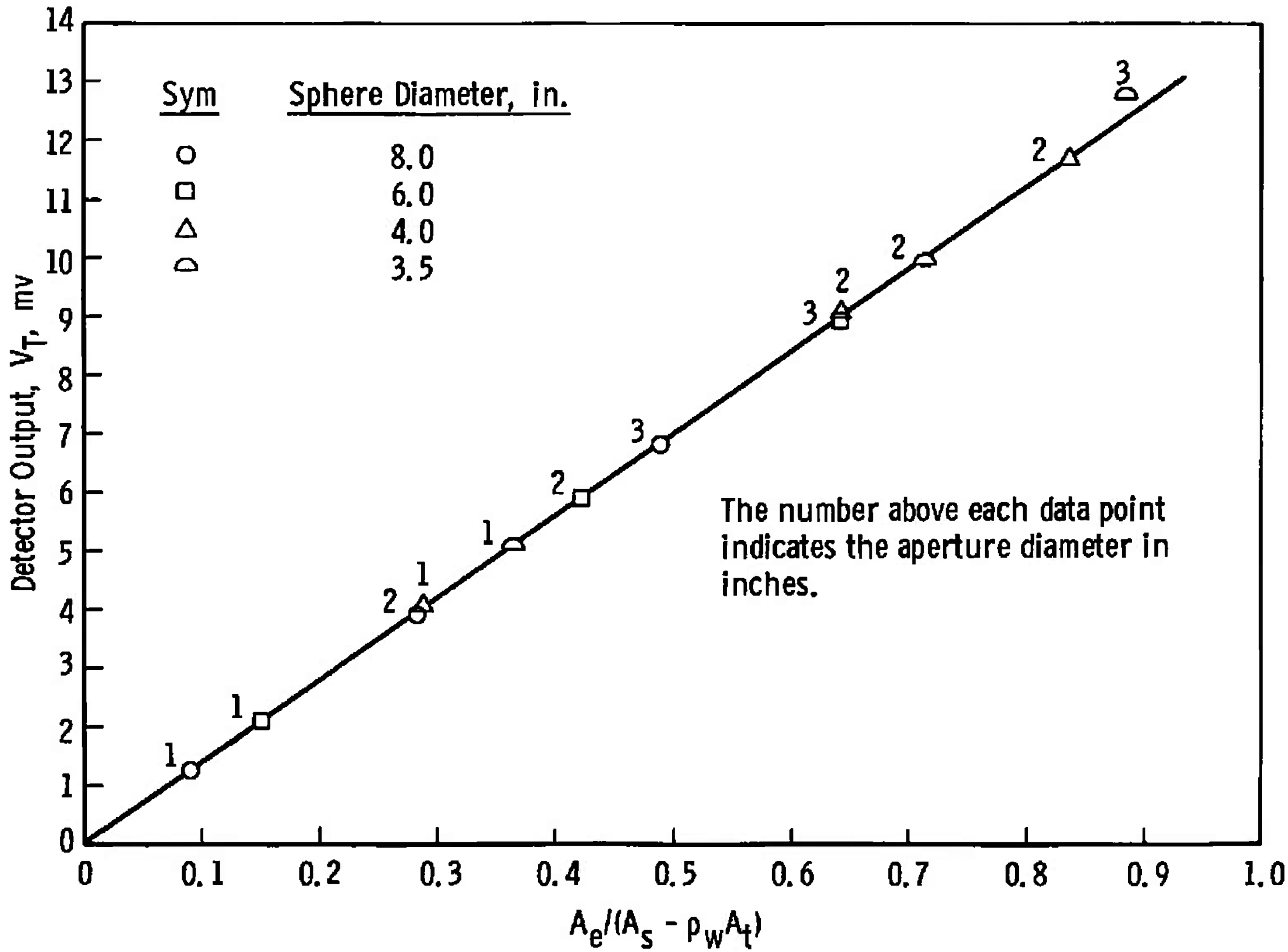
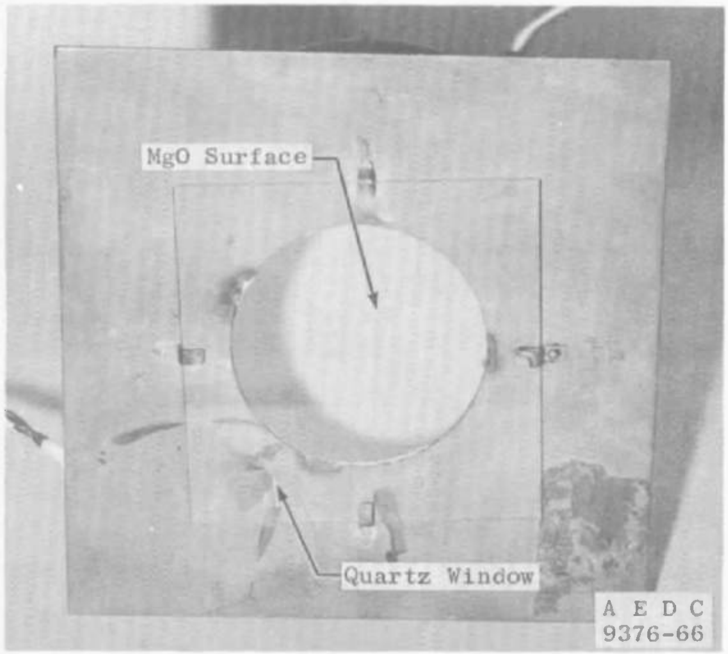
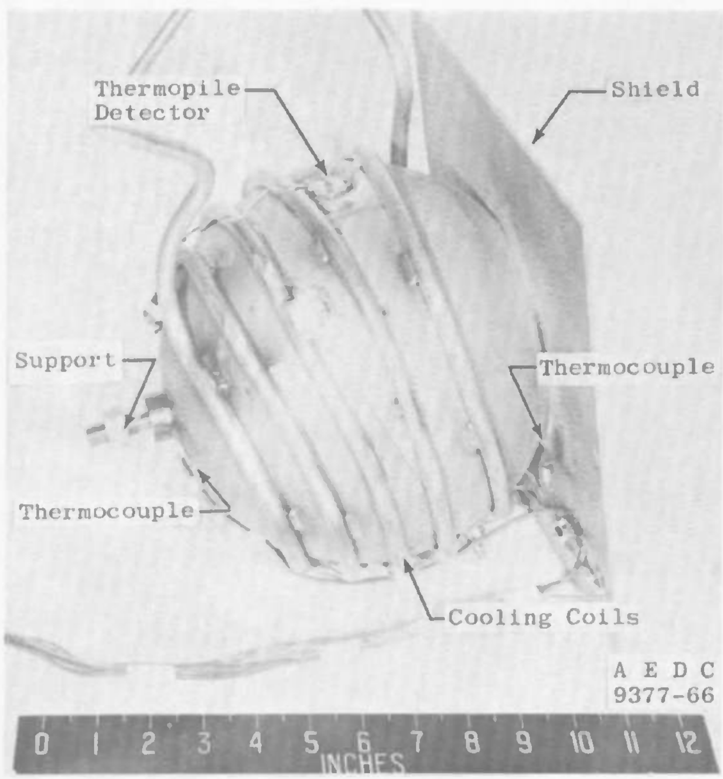


Fig. 2 Experimental Verification of Monitor Theory



a. Front View



b. Side View

Fig. 3 Radiation Intensity and Uniformity Monitor

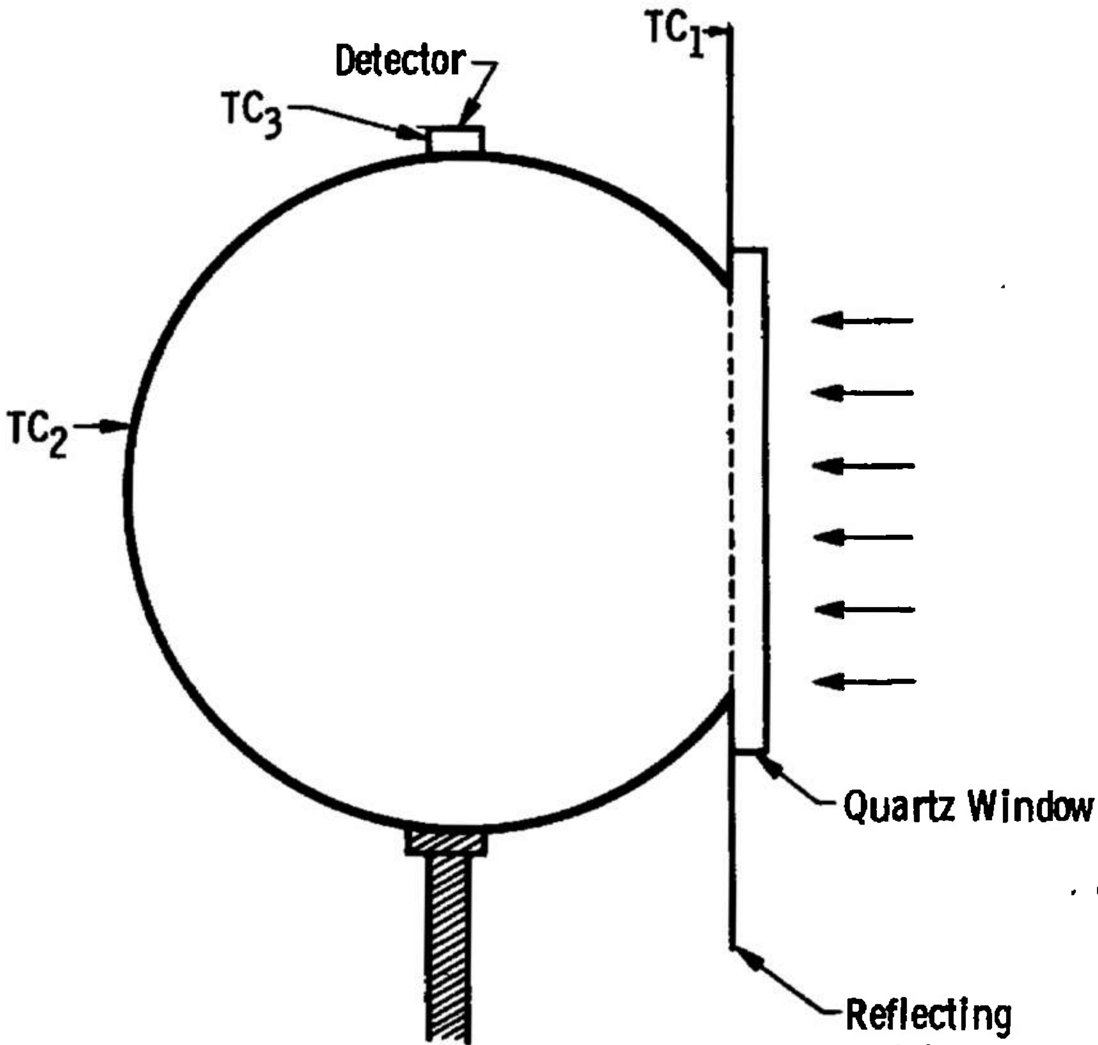


Fig. 4 Schematic of 8-in.-diam Monitor

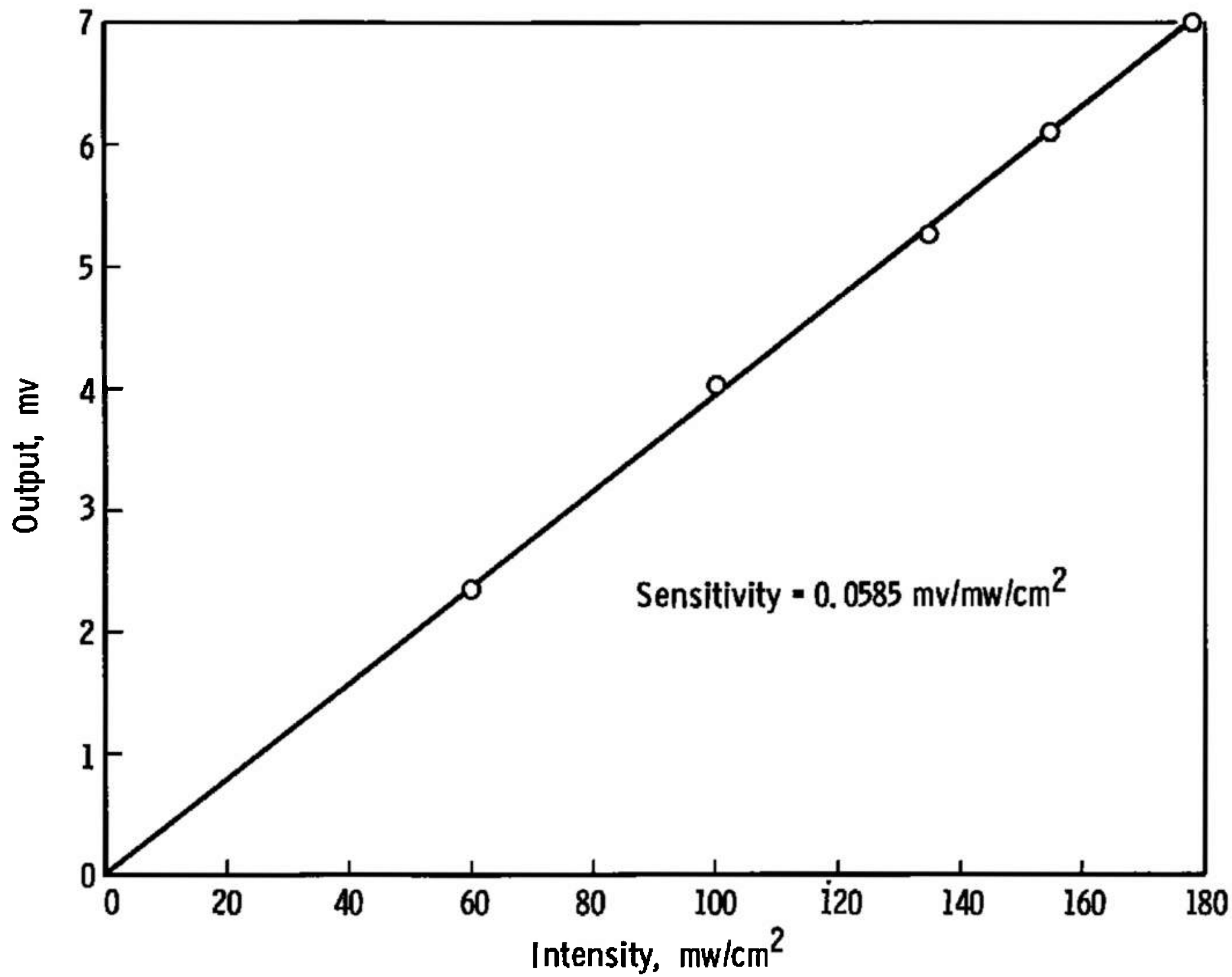


Fig. 5 Calibration of 8-in.-diam Monitor

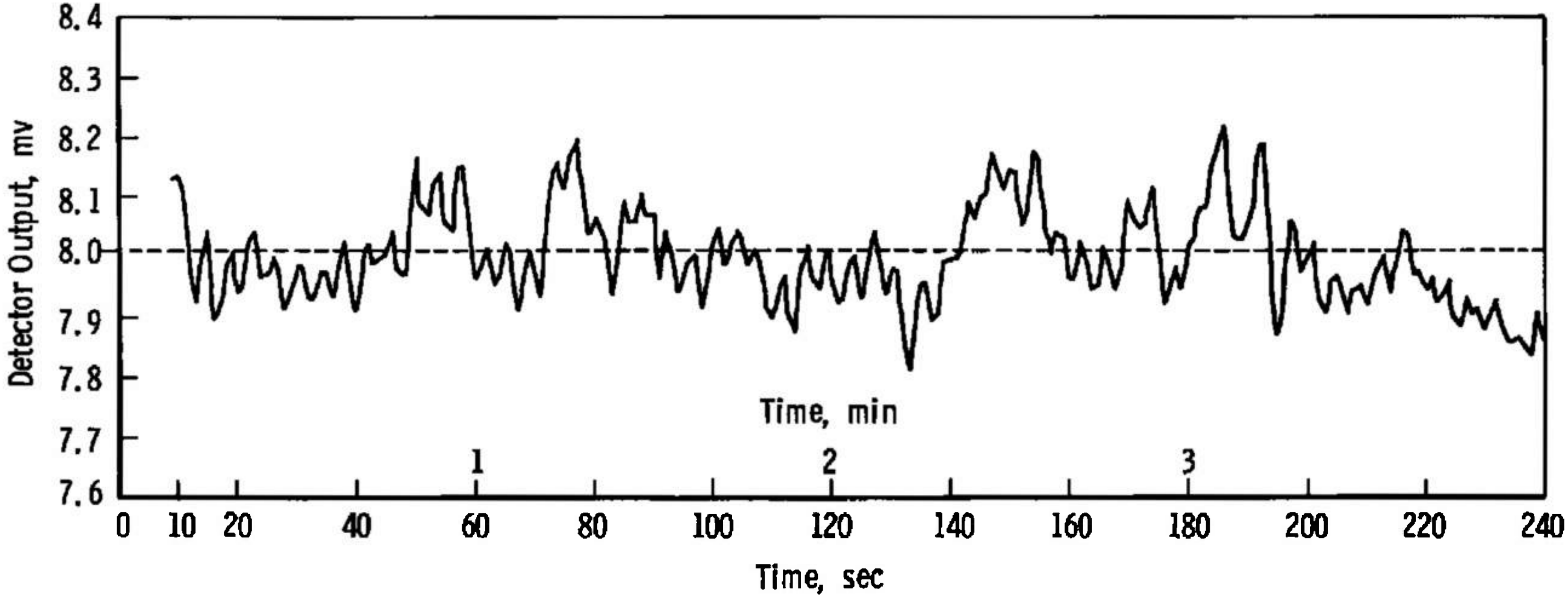


Fig. 6 Monitor Output Variation with Time

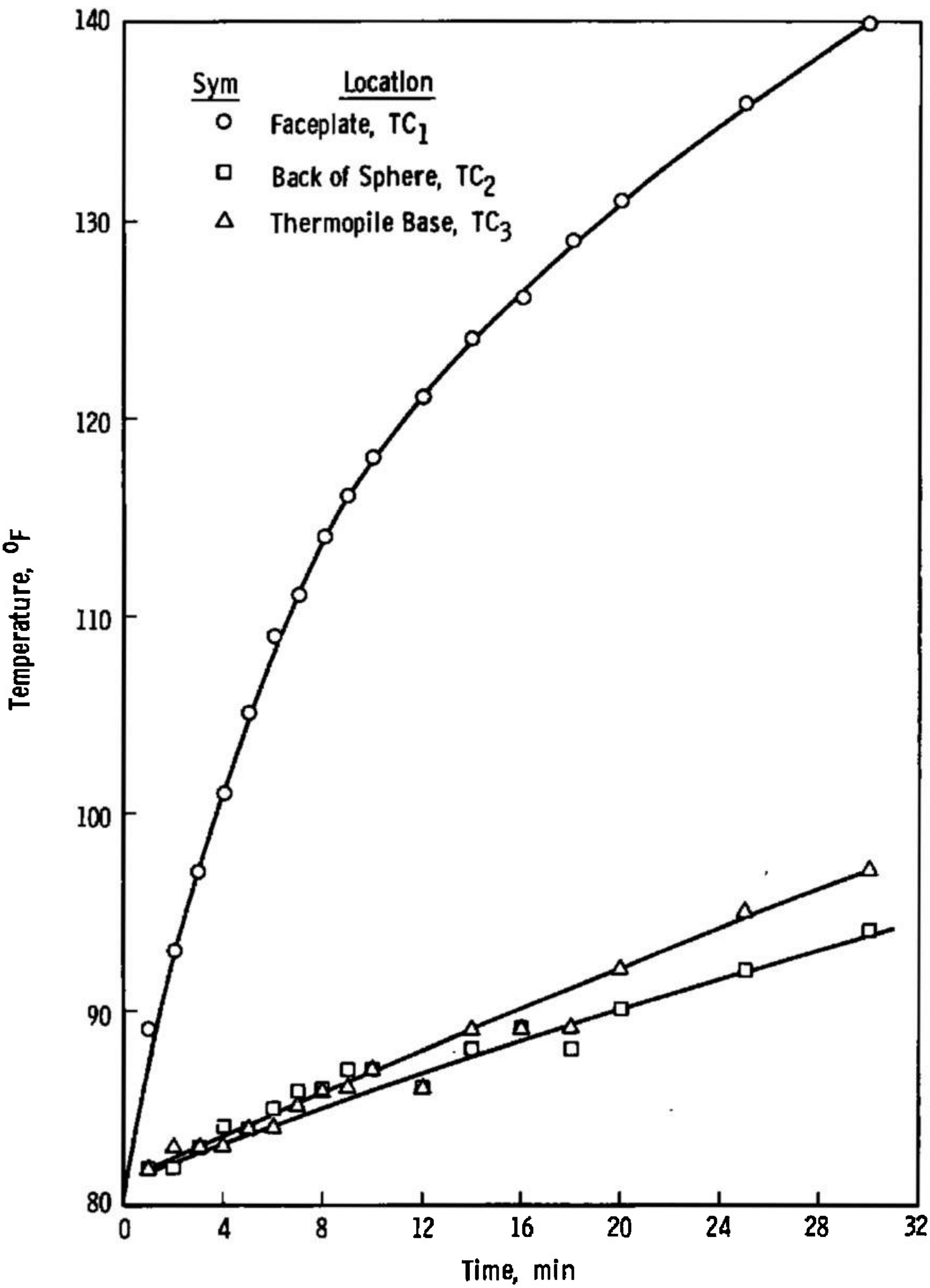


Fig. 7 Monitor Temperature Variation with Time

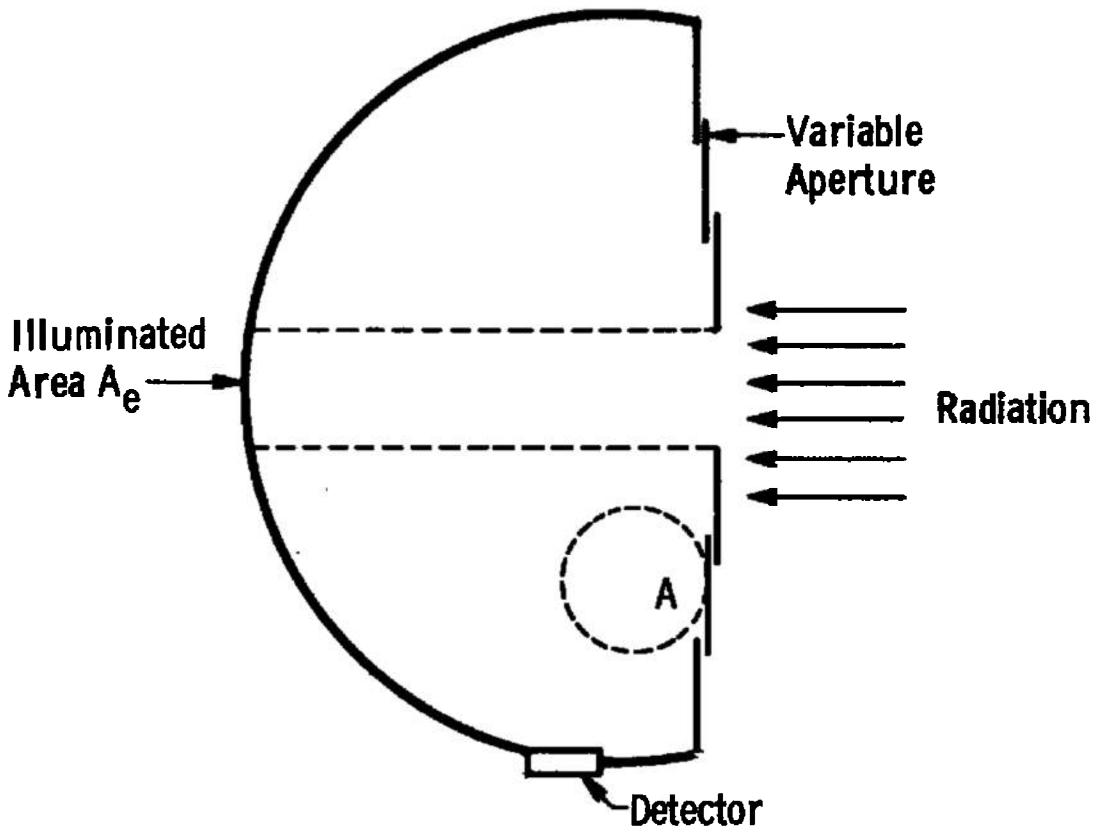


Fig. 8 Monitor with Variable Aperture

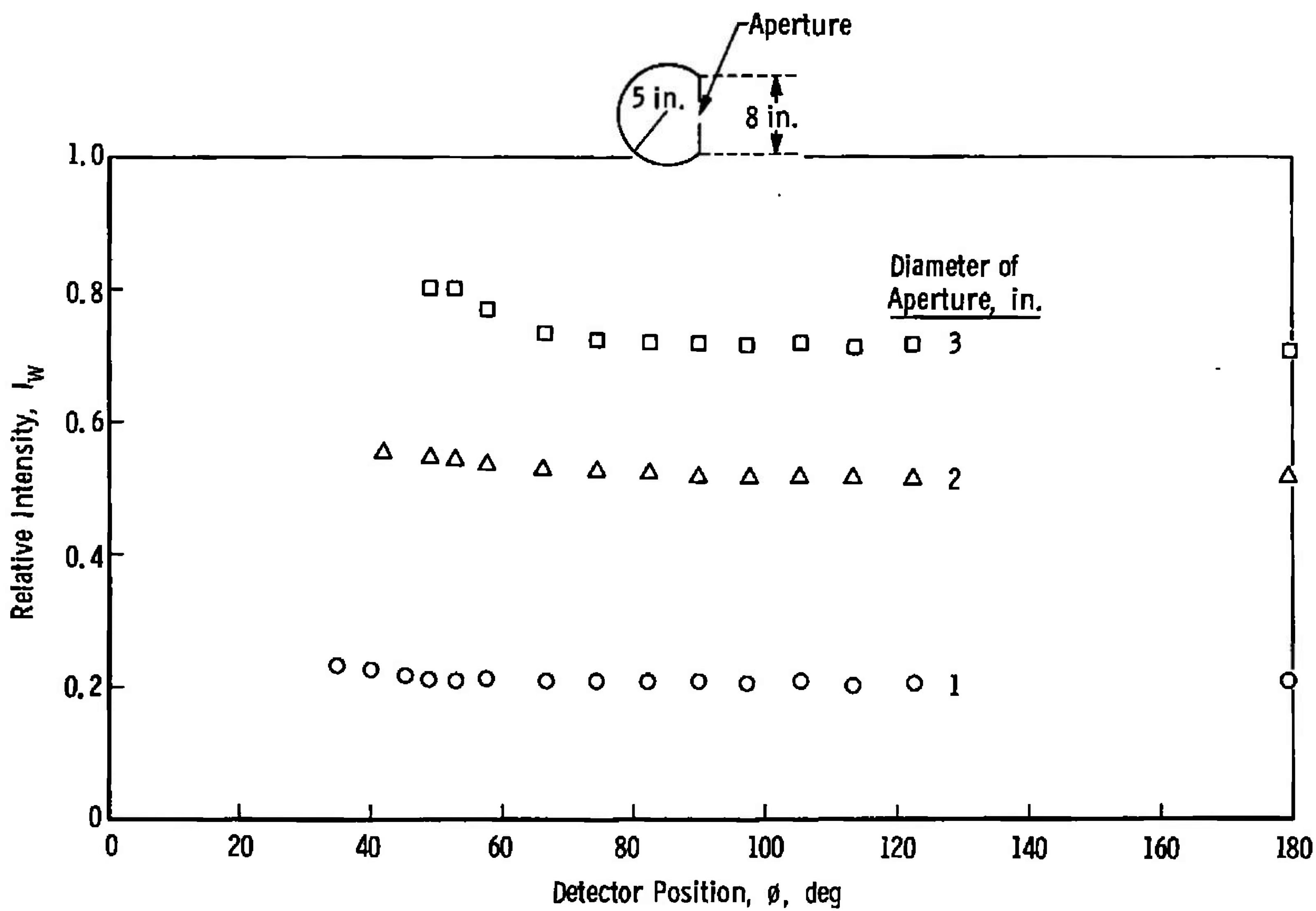


Fig. 9 Intensity Distribution

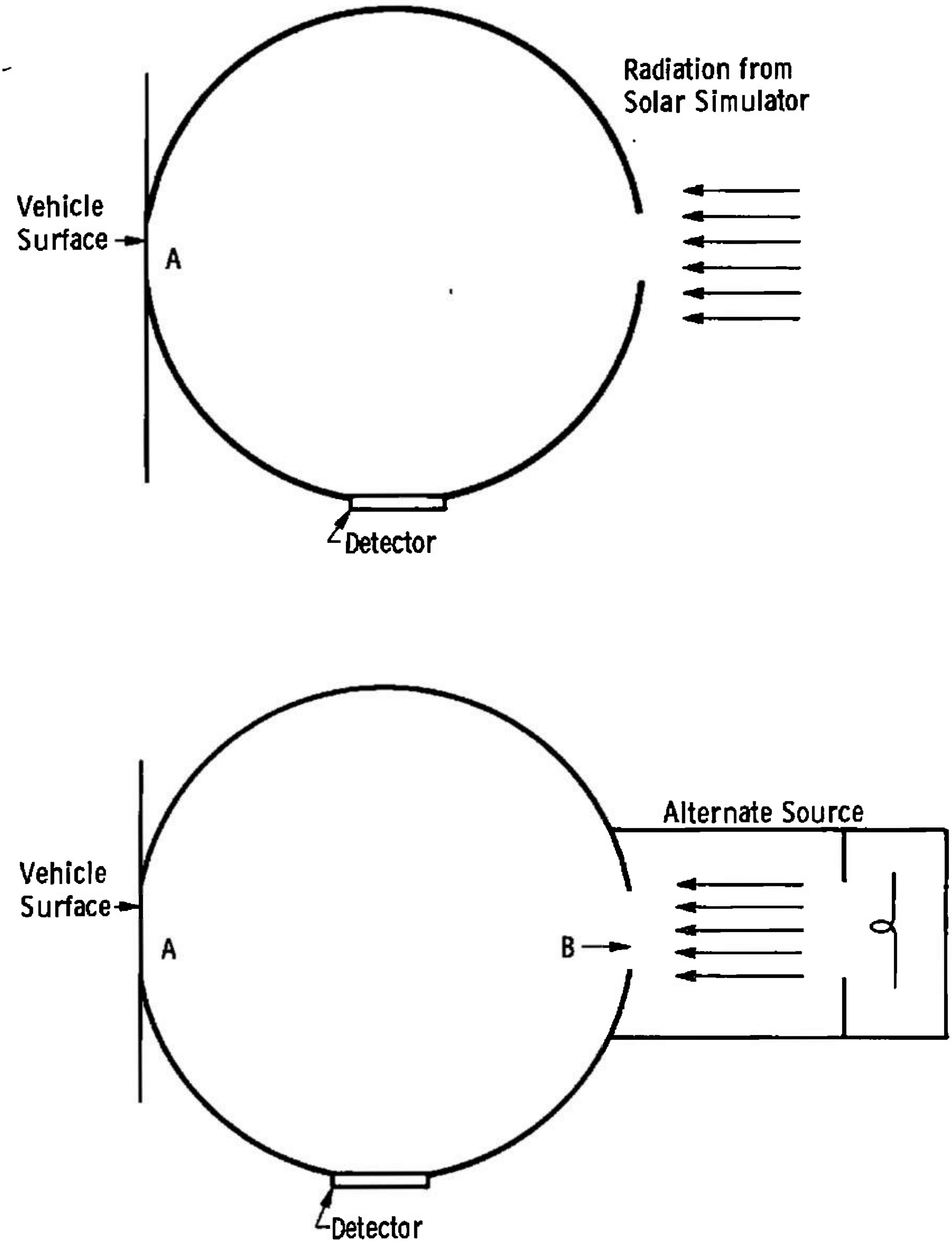


Fig. 10 Portable Reflectometer

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13. ABSTRACT

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optical measurements						
integrating sphere						
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